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Volume change behaviour of swelling and non-swelling clays upon inundation with water and a low dielectric constant fluid

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**Volume change behaviour of swelling and non-swelling clays upon inundation with
water and a low dielectric constant fluid**

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Abstract: Studies of the volume change behaviour of saturated and unsaturated fine-grained soils upon exposure to various types of fluid are of significant interest while dealing with contaminated soils. In this study, the one-dimensional volume change behaviour of two clays (Spergau kaolin and Calcigel bentonite) with dominant minerals as kaolinite and montmorillonite was studied by inundating several initially unsaturated and saturated clay specimens with water and a non-polar organic liquid (heptane). For both cases, applied vertical pressures of 25 and 100 kPa were considered under oedometric conditions. The magnitude of compression and swelling deformations of the clays were found to be strongly dependent upon the mineralogy of clays, dielectric properties of the pore-fluid, initial compaction conditions, and applied stress during the wetting process. The test results indicated distinct interactions between unsaturated clays and water. Specimens of Spergau kaolin exhibited compression with water, whereas specimens of Calcigel bentonite exhibited swelling. Compression and swelling deformations of the clays with heptane as the inundating liquid remained within about $\pm 1.0\%$ for both clays indicating a very minor interaction between unsaturated clays and molecules of this non-polar organic liquid. The test results emphasized the significance of attractive and repulsive forces and their impact on the volume change behaviour of clays of different mineralogy.

Keywords: minerology of clays; swelling; compression; pore-fluid; waste containment; laboratory tests

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1. Introduction

Studies of the volume change behaviour of fine-grained soils upon exposure to various types of fluid are of great interest, particularly while dealing with contaminated soils. Contamination of soils in vadose zone may occur due to industrial activity, agricultural chemicals, gasoline spillage, and improper disposal of waste. Similarly, mitigation strategies adopted for soils contaminated with various organic contaminants demands understanding of the soil-contaminant interaction at various stress states of soils.

The physico-chemical interaction between soil particles and their influence on the volume change behaviour of fine grained soils depends upon the clay mineralogy and the pore fluid characteristics (e.g., Sridharan and Rao, 1973; Lagaly 1989; Mitchell and Soga 2005). Organic fluids, chemicals, and petroleum products usually possess dielectric constant values far lower than that of water. A review of the literature suggests that the influence of organic fluids on the plasticity properties, compressibility, shear strength, and hydraulic conductivity of saturated clays has been studied in detail by several researchers in the past (Mesri and Olson 1971; Sridharan and Rao 1973; Sridharan and Rao 1979; Fernandez and Quigley 1985; Lagaly 1989; Shang *et al.* 1994; Kaya and de Brito Galvao 1998; Kaya and Fang 2005). However, studies concerning the volume change behaviour of compacted unsaturated clays upon exposure to organic fluids, particularly in the context of the influence of mineralogy, compaction conditions, and applied external stress are scarce in the literature. In this study, laboratory one-dimensional swell or compression tests were carried out on two clays with two types of fluid and at two different stress levels for studying the impacts of polar and non-polar fluids, the magnitude of an applied stress, and initial compaction conditions on the volume change behaviour of clays.

2. Background

During the wetting process and under a constant applied stress, the volume change of unsaturated fine-grained soils is accompanied by a decrease in the shearing resistance at inter-particle level brought about by a reduction in the soil suction, and by the changes in the magnitude of the physico-chemical forces. As a result, a soil may exhibit swelling or compression, or even the volume change may not occur under specific stress and hydraulic boundary conditions. The physico-chemical forces are comprised of the electrical attractive and the repulsive forces (Verwey and Overbeek 1948; Bolt 1956; van Olphen 1977; Sridharan and Jayadeva 1982; Heuckel 1992; Mitchell and Soga 2005). The repulsive forces that may get generated within clay-fluid systems are due to the interaction of electrical double layers around the clay particles and hydration of ions and surfaces of clay particles (Madsen and Müller-Vonmoos 1989; Laird 2006; Baille et al. 2010). These forces tend to cause an increase in the volume of clays. The interaction between the edges of clay particles with the negatively charged surfaces are electrostatic (Columbic) in nature. The primary and secondary bonding (hydrogen bond and van der Waals bond) are the other possible sources of attractive force that govern the shear resistance at inter-particle level. The short range inter-particle force exists at very close spacing, whereas the long-range attractive forces (van der Waals force) are considered to be sensitive to applied force and pore fluid properties.

The mobilised physico-chemical forces within clay systems to a great extent depend upon the physical and chemical properties of the clays (i.e., specific surface area and type and amount of exchangeable cations present in the clay), the bulk fluid properties (i.e., solvent type, concentration, dielectric properties, and pH), the applied external stress, the soil suction, the initial compaction conditions of the clay (i.e., dry density and water content), and the

temperature (Sridharan and Jayadeva 1982). The physico-chemical forces influence the fabric in fine-grained soils, which in turn regulates the hydraulic conductivity, compressibility, stiffness, and shear strength (Sridharan, 1991, Sridharan and Rao 1979; Fernandez and Quigley 1985; Chen et al. 2000; Santamarina et al. 2001; Mitchell and Soga 2005; Wang and Siu 2006). The fine-grained soil system is complex and the individual effects of various parameters influencing the repulsive and attractive pressures cannot be readily separated. However, it has been brought out in the literature that the dielectric constant of the pore medium plays an important role in that, the attractive force varies inversely and the repulsive force varies directly with the dielectric constant of the pore medium (Verwey and Overbeek 1948; van Olphen 1977; and Sridharan and Rao 1973 and 1979).

Adsorption of water molecules in the silicate layers of clay minerals tends to eliminate the attractive pressure at the edge-face contacts in flocculated clay structure. Development of the repulsive pressure during the wetting process causes further decrease in the attractive pressure between the clay particles. A decrease in the attractive pressure gets manifested on a reduction in the shearing resistance due to a reduction in effective contact stress. Both the mobilized repulsive and attractive pressures are strongly dependent upon the characteristics of the hydrating fluid. Partially saturated and fully saturated clay systems possess attractive pressures lower than that occur in dry clays due to a partial or completion of the surface and ion hydration processes (Sridharan 1968).

The exchangeable cations in clay are soluble in polar fluids (e.g., water and polar organic liquids); however, are insoluble in non-polar organic liquids (e.g., heptane, toluene etc.). The adsorption of polar organic liquid molecules in the interlayers occurs either as replacement to water molecules in partially saturated clay systems or via the exchangeable

cations in fully dry clays (Grim 1968; Theng 1974; and van Olphen 1977). Sorption of non-polar organic molecules in the interlayers of dry clays is usually insignificant, whereas the process can be very slow or only limited adsorption may take place in the interlayers of partially saturated clays (Grim 1968; Theng 1974; and Amarashinghe et al. 2009).

3. Materials and methods

Spergau kaolin and Calcigel benonite, both clays from Germany, were used in this investigation. The properties of the clays are given in Table 1. The chosen clays possess a wide range of physical and chemical properties. X-ray diffraction studies indicated that about 60% of the minerals in Calcigel bentonite were montmorillonite, whereas the remaining were quartz, feldspar, dolomite, and calcite. Spergau kaolin was found to contain about 72% kaolinite, 16% quartz, and 10% muscovite. Studies of the cation exchange complexes of the clays indicated that more than 85% of the exchangeable cations in Calcigel bentonite were Ca^{+2} and Mg^{+2} with small fractions of Na^{+} and other ions (Schanz and Tripathy 2009). Spergau kaolin was found to contain Ca^{+2} , Mg^{+2} , and K^{+} .

One-dimensional swell and compression tests (ASTM 1986) were carried out in conventional oedometers. All tests were carried out at a temperature of 20 ± 2 °C. Compacted clay specimens were prepared at various water contents including from oven-dried clay powder. Distilled water was used for preparing the clay-water mixtures. The clay-water mixtures were stored in air-tight plastic bags for about a week in the laboratory for moisture equilibration to take place. Compacted clay specimens were prepared corresponding to predetermined dry densities with gentle tamping on the clay-water mixtures within the oedometer rings. Extreme precautions were exercised in order to minimize the errors due to

side friction by lubricating the specimen rings with technical grade silicon grease. Filter papers were used at the top and bottom of the specimens.

The details of the specimens tested for Spergau kaolin and Calcigel bentonite are given in Tables 2 and 3, respectively. For both clays and for each combination of water content-dry density, two different vertical pressures levels were considered, such as 25 and 100 kPa. For the clay specimens that were prepared from oven dried clay powder and at low initial water contents (i.e., 0 and 12% for Spergau kaolin and 0 and 9.0% for Calcigel bentonite), the targeted external loads were applied in a single step loading process, whereas for the specimens that were prepared at higher water contents (61.5% for Spergau kaolin and 55.2 and 64.3% for Calcigel bentonite), a load increment ratio of one was adopted to attain the required vertical pressure levels. The incremental loads were applied after an elapsed time of more than three hours or upon completion of the primary consolidation phase, which ever occurred earlier. Following the loading process, the specimens were inundated either with water or heptane (C_7H_{16}). For every applied vertical stress, time-vertical deformation readings were monitored using dial gauges of sensitivity of 0.001 mm and a total run of 25 mm. Similarly, the time-deformation readings (compression or swelling) were monitored until the equilibrium conditions were attained. At each compaction conditions (see Tables 2 and 3), four specimens were tested. In total, thirty-six clay specimens were tested, sixteen for Spergau kaolin and twenty for Calcigel bentonite.

The dielectric constant of water is 80.4, whereas that of heptane is 1.92 as against the dielectric constant of air of 1.0. Additionally, water is a polar liquid, whereas heptane is a non-polar organic liquid. Heptane is a highly flammable solvent. Extreme care was exercised while handling the solvent by wearing gloves and a medical mask. The oedometer tests were

carried out in an isolated room with appropriate ventilation system. Similarly, appropriate disposal methods were undertaken after completion of the laboratory tests.

Prior to testing for the clay specimens, the pressure-deformation characteristics of the oedometers used were studied using a steel dummy following the procedure suggested by ASTM (1998). Based on the pressure-deformation characteristics of the oedometers used, the measured heights of the specimens at each loading steps were corrected for calculating the actual vertical deformations. The vertical deformation at equilibrium under any given applied vertical pressure is defined as the ratio of the change in height of a specimen upon either swelling or compression to the height of the specimens prior to inundation and is expressed as a percentage. The void ratio changes during swelling or compression of the specimens were calculated based on height of solids method.

4. Presentation of experimental results

4.1 Volume change behaviour of Spergau kaolin

The elapsed time versus void ratio plots for Spergau kaolin specimens at four different initial placement conditions, two different applied vertical pressures (i.e., 25 and 100 kPa), and with water and heptane as the inundating fluids are shown in Figs. 1 and 2. The vertical deformations of the specimens at equilibrium are shown in Table 2.

Following inundation of the specimens either with water or heptane, except two specimens that exhibited a small volume increase upon inundated with heptane (water contents of 0 and 23.3%, dry density 1.11 Mg/m^3), all other specimens exhibited compression

(Table 2, Figs. 1 and 2). The compression deformation of the specimens occurred within about 15 to 25 minutes following the inundation process in all cases.

The test results of the initially unsaturated specimens showed three distinct trends in terms of the volume change (Table 2, Figs. 1a, 1b and 2a), such as (i) at any applied vertical pressure (25 or 100 kPa), the compression deformation was significantly smaller for the specimens that were inundated with heptane than that occurred with water, (ii) the vertical deformation decreased with an increase in the initial compaction dry density and with an increase in the water content for both inundating fluid types, and (iii) the vertical deformation increased with an increase in the applied stress for both fluid types.

For the saturated clay specimens with an initial water content of 61.5% (Fig. 2b), the vertical deformations at any given applied pressure and with both water and heptane as the inundating fluids were very nearly similar clearly indicating that the pore-fluid type has limited impact on the volume change behaviour of saturated kaolinites.

4.2 Volume change behaviour of Calcigel bentonite

The elapsed time versus void ratio plots for the specimens of Calcigel bentonite at five different initial placement conditions, two different applied vertical pressures (i.e., 25 and 100 kPa), and with water and heptane as the inundating fluids are shown in Figs. 3, 4, and 5. The initial compaction conditions of the specimens, the inundation fluids used, and the applied vertical pressures are shown in Figs. 3 to 5. The vertical deformations of the specimens at equilibrium are given in Table 3.

Following inundation either with water or heptane, except four specimens with high initial void ratios of 1.94 and 1.8 that underwent slight compression at an applied stress of 100 kPa, all other specimens (Table 3) exhibited swelling. The test results of the initially unsaturated specimens showed three distinct trends in terms of the volume change (Figs. 3 to 5 and Table 3), such as (i) the swelling deformation was significantly greater for the specimens that were inundated with water as against their counterparts that were inundated with heptane, (ii) with an increase in the applied stress during inundation with any fluid, the deformation behaviour of the specimens was accompanied by either a decrease in the swelling deformation or an increase in the compression deformation, or even specimens that exhibited swelling at 25 kPa, underwent compression at 100 kPa, (iii) for the specimens with an initial water content of 0%, an increase in the compaction dry density caused an increase in swelling deformation, whereas swelling deformation decreased with an increase in the initial water content for the same compaction dry density (see results for dry density of 1.10 Mg/m³ in Table 3).

The test results presented in Figs. 3, 4, and 5 clearly indicated that unlike the deformation behaviour of the unsaturated specimens of Spergau kaolin, in which case the compression deformation invariably increased with an increase in applied vertical pressure and for both inundation fluids used (Figs. 1 and 2, Table 2), the deformation behaviour was found to be reversed in the case of Calcigel bentonite. In the latter case, the swelling deformation decreased with an increase in the vertical pressure. Additionally, the influence of fluid type and applied vertical pressure was found to be quite significant on the volume change behaviour of the specimens that were initially saturated (Fig. 5 and Table 3). This was not evident in the case of saturated Spergau kaolin specimens (Figs. 2b and Table 2).

5. Influence of physico-chemical forces on the volume change of clays

Table 4 summarises the influence of a decrease in the dielectric constant of the inundating fluid, an increase in the applied stress during the inundation process, an increase in the compaction water content, and an increase in the compaction dry density on the vertical deformation of clay specimens observed in this study. The possible reasons for the volume change of clays are presented in Table 4.

Further, the results can also be explained by the changes in the effective stress that has been brought out by changes in normal stress, repulsive and attractive forces. It has been now widely accepted that Terzaghi's concept of effective stress provides a satisfactory basis for understanding the strength and deformation characteristics of saturated soils, which can be stated as:

$$\sigma' = \sigma - u \quad (1)$$

where σ' = effective stress, σ = applied external stress or the total stress and u = pore water pressure.

It may be noted that σ' is the contact stress at mineral to mineral contact zone, which is also called inter-granular stress. While one can discuss at greater length the nature of this contact, for purpose of brevity, it can be said that the role of contact is to transfer the stress. It has been brought out earlier that both electrical attractive and repulsive forces exist between clay particles. Since the fine grained soils are normally composed of clays, the existence of attractive and repulsive forces in the soil-water system is inevitable. The studies of Sridharan

(1968) and Sridharan and Rao (1973, 1979) resulted in the proposition of modified effective stress concept as given in eq. (2).

$$\bar{c} = \bar{\bar{\sigma}} a_m = \sigma - u - R + A \quad (2)$$

For a saturated system, where \bar{c} is the average contact stress, $\bar{\bar{\sigma}}$ is actual contact stress at mineral - to - mineral level, a_m is area fraction over which $\bar{\bar{\sigma}}$ acts or percentage area through which $\bar{\bar{\sigma}}$ acts (non-dimensional), σ = the external applied stress, u = pore water pressure, R = average repulsive pressure acting throughout the area, A = average attractive pressure acting throughout the area.

Equation (2) can be written as

$$\bar{c} = \bar{\bar{\sigma}} a_m = \sigma' + \sigma'' \quad (3)$$

where σ'' is the intrinsic effective stress and σ' is the conventional effective stress.

It may further be stated that the effect of σ and A is to bring the particles closer to each other. The effect of positive pore water pressure and R is to keep the particles away from each other. If the pore water pressure is negative (i.e., capillary pressure operative in partly saturated soils), its role is to bring the particles closer to each other. The average contact stress or the intergranular stress (\bar{c}) between particles, is defined as the modified effective stress and it is hypothesised that \bar{c} is the stress controlling the shearing resistance and volume changes that take place in soil-water system. In fine-grained soils / clayey soils, the attractive and repulsive forces cannot be neglected, especially when the water content and the

soil plasticity are high. Since the clay-water system is complex, quantitative determination of R and A becomes difficult for real systems. However, qualitative evaluation could be done. The validity of eqns. (2) and (3) have been qualitatively studied extensively considering the volume change behaviour (Sridharan and Rao 1973; Sridharan et al. 1973; Sridharan 2003:), the strength behaviour (Sridharan et al. 1971; Sridharan and Rao 1979; Allam and Sridharan 1981; Sridharan et al. 1983; Sridharan and Prakash, 1999b), the shrinkage phenomena (Sridharan and Rao 1971), the secondary compression behaviour (Sridharan and Rao 1982) and the sediment formation (Sridharan and Prakash 1999a).

The thickness of the electrical double layer that is formed around the clay particles are influenced by several factors (Mitchell and Soga 2005), such as the characteristics of the hydrating fluid, the type and amount of exchangeable cation present in the clay, the specific surface area, the applied external stress, and the temperature (Verwey and Overbeek 1948; van Olphen 1977; Sridharan and Rao 1979; and Sridharan and Jayadeva 1982). The thickness of the electrical double layer controls the swelling, compressibility, shear strength, and hydraulic conductivity in clays. The factors that cause an increase in the thickness of electrical double layer are also responsible for a higher magnitude of swelling deformation in expansive clays resulting in a decrease in the modified effective stress. Similarly, the factors that cause a decrease in the thickness of electrical double layer aid in an increasing the modified effective stress and increasing the shearing resistance and cause a decrease in the compressibility and the hydraulic conductivity.

The attractive force varies inversely and the repulsive force varies directly with the dielectric constant of the pore fluid (Sridharan and Rao 1973 and 1979). Therefore, a decrease in the dielectric constant of the pore fluid caused two opposite effects for both clays

in this study when the inundating fluid was heptane, such as an increase in the attractive pressure and a decrease in the repulsive pressure and thus an increase in the modified effective stress. A greater mobilised attractive pressure with heptane as the inundating fluid caused an increase in the modified effective stress and two distinct effects, such as that (i) the interparticle shearing resistance did not decrease as that occurred with water as the inundating fluid thereby causing a lesser compression of the specimens of Spergau kaolin and (ii) since the electrical double layer thickness was reduced in case of Calcigel bentonite, the clay exhibited a lesser swelling as compared to that occurred with water as the inundating fluid. The magnitude of applied stress on the clays can be considered to have two effects, such as an increase in the applied stress acts against the interparticle shearing resistance to cause a greater deformation in case of Spergau kaolin and it acts as a restraint against the expansion of the electrical double layer thereby causing a reduction in the swelling deformation in case of Calcigel bentonite.

An increase in the initial compaction water content and its influence on the deformation behaviour of the clays can be considered separately for the two inundating fluids considered in this study (i.e., water and heptane). An increase in the compaction water content causes a reduction in the inter-particle shearing resistance since the attractive pressure is inversely proportional to the dielectric constant of the pore fluid. Additionally, an increase in the compaction water content causes the hydration of the surfaces and the ions. A further increase in the compaction water content above that is required for surface and ion hydration aids in the formation of the electrical double layer. The increased volume of the clay due to the expansion of the electrical double layer depends upon the volume of water available and the type of clay mineral present. With the inundating fluid as water, the changes in the vertical deformation in case Spergau kaolin was found to be minor since the pore fluid

remained unchanged. The swelling deformation in the case of Calcigel bentonite also reduced since a part of the swelling process was already completed during the specimen preparation stage. The clay specimens of Calcigel bentonite exhibited further swelling primarily due to the available of water which caused a further expansion of the electrical double layer.

Replacement of water by heptane can be considered when the inundating fluid used was heptane. This would tend to cause an increase in the inter-particle shearing resistance primarily due to an increase in the attractive pressure and a decrease in thickness of the electrical double layer. A replacement of molecules of water by heptane for kaolinite is expected to cause no significant change in terms of the deformation, but due to a change in the magnitude of the attractive pressure the clay may tend to flocculate causing an increase in the volume (see test results for specimens at water content = 12% in Table 2). A decrease in the thickness of electrical double layer in case of Calcigel bentonite reduced the swelling deformation of the clay. Saturated specimens exhibited slight swelling deformation which indicated that replacement of water with heptane will increase the electrical attractive forces resulting in a relatively flocculent fabric which tend to get eliminated as the applied stress increased (see test results of initially saturated specimens in Table 3).

An increase in the compaction dry density is associated with an increase in the applied stress that overcomes the inter-particle shearing resistance and tends to produce a more oriented fabric perpendicular to the direction of the applied load. A decrease in the void ratio brings the clay particles closer towards each other which in turn, causes an increase in the attractive pressure. Ignoring the orientation of clay particles and the difference in the magnitude of the attractive pressure, under any given applied stress, clay specimens with different initial compaction dry densities but with same initial water content may exhibit

different vertical deformations, but should attain the same void ratio upon saturation. A decrease in the compression deformation in case of Spergau kaolin is attributed due to an increase in the attractive pressure, whereas an increase in the swelling deformation due to an increase in the compaction dry density in the case of Calcigel bentonite is attributed due to expansion of the electrical double layer in response to the applied stress during the inundation process.

Thus it can be seen that the volume change (compression or swelling) behaviour of both the clays in this study can be explained by the changes in the intrinsic effective stress, defined by equations (2) and (3), brought out by the changes in the electrical attractive and repulsive pressures (influenced by the fluid types by their di-electric constant values), the negative pore pressures and the externally applied stress.

6. Conclusions

The one-dimensional volume change behaviour of kaolinite and montmorillonite-rich clays is presented in this paper. Several initially unsaturated and saturated clay specimens were inundated either with water or heptane at applied vertical pressures of 25 and 100 kPa.

The test results clearly showed that the physico-chemical forces within the clay-fluid systems are significantly influenced by the mineralogy of clays, the properties of the hydrating and the inundating fluids, the compaction dry density and water content, and the applied stress during the inundation process. The kaolinite-rich clay in this study exhibited low compression with both water and heptane, whereas the montmorillonite clay exhibited significant swelling (up to 23%) with water, whereas in the kaolinite clay exhibited swelling

up to about 0.9%. The changes in the volume of the clays were found to be much smaller with heptane (attributed to strong electrical attractive forces) as compared that occurred with water. The volume change behaviour of the clays are explained in the light of the modified effective stress and the interplay of attractive and repulsive pressures.

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- 481

482 **Table 1** Properties of the clays used in the study

Properties	Spergau kaolin	Calcigel bentonite
Specific gravity of soil solids, G_s	2.62	2.80
Liquid limit, w_L (%)	53.4	178.0
Plastic limit, w_P (%)	30.1	56.0
Shrinkage limit, w_S (%)	22.3	8.8
Specific surface area, S (m^2/g)	14.0	650.0
Base exchange capacity, B (meq/100g)	8.0	74.0

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485 **Table 2** Details of Speregau kaolin specimens tested

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Initial compaction conditions					Inundation	Vertical deformation
					fluid	(%) at applied vertical stress
Water	Dry	Void	Degree	of		25 kPa
content (%)	density	ratio	saturation			100
	(Mg/m ³)		(%)			kPa
0	1.02	1.58	0		Water	-13.42
0	1.02	1.58	0		Heptane	-0.23
0	1.11	1.35	0		Water	-8.14
0	1.11	1.35	0		Heptane	0.43
12.0	1.11	1.35	23.3		Water	-7.57
12.0	1.11	1.35	23.3		Heptane	0.34
61.5	1.00	1.61	100		Water	-0.43
61.5	1.00	1.61	100		Heptane	-0.44

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489 **Table 3** Details of Calcigel bentonite specimens tested

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Initial compaction conditions					Inundation	Vertical deformation
					fluid	(%) at applied vertical stress
Water	Dry	Void	Degree	of		25 kPa
content (%)	density	ratio	saturation			100 kPa
	(Mg/m ³)					
0	0.95	1.94	0		Water	16.01
0	0.95	1.94	0		Heptane	-0.49
0	1.10	1.54	0		Water	22.80
0	1.10	1.54	0		Heptane	0.91
9.0	1.10	1.54	16.4		Water	19.87
9.0	1.10	1.54	16.4		Heptane	0.83
55.2	1.10	1.54	100		Water	7.6
55.2	1.10	1.54	100		Heptane	0.16
64.3	1.00	1.80	100		Water	3.2
64.3	1.00	1.80	100		Heptane	0.29

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492

Table 4 Influence of various factors on the vertical deformation of unsaturated clays upon saturated under applied stress

Reference	Vertical deformation		Remarks
	Kaolinite	Montmorillonite	
Decrease in dielectric constant of inundating fluid	Compression decreases	Swelling decreases	Attractive pressure increases/Double layer thickness decreases
Increase in applied stress during inundation	Compression increases	Swelling decreases	Interparticle shearing resistance exceeded/Double layer expansion restricted
Increase in compaction water content	Compression decreases	Swelling decreases	Attractive pressure decreases/Surface and ion hydration processes and development of double layer
Increase in compaction dry density	Compression decreases	Swelling increases	Attractive pressure increases/Repulsive pressure increases

497 **Figure captions**

498 **Fig. 1** Water content versus total suction plot for the clays used in this study

499 **Fig. 2** Time-deformation behaviour of Spergau kaolin specimens

500 **Fig. 3** Summary of vertical deformations of Spergau kaolin specimens

501 **Fig. 4** Time-deformation behaviour of Calcigel bentonite specimens

502 **Fig. 5** Summary of vertical deformations of Calcigel bentonite specimens

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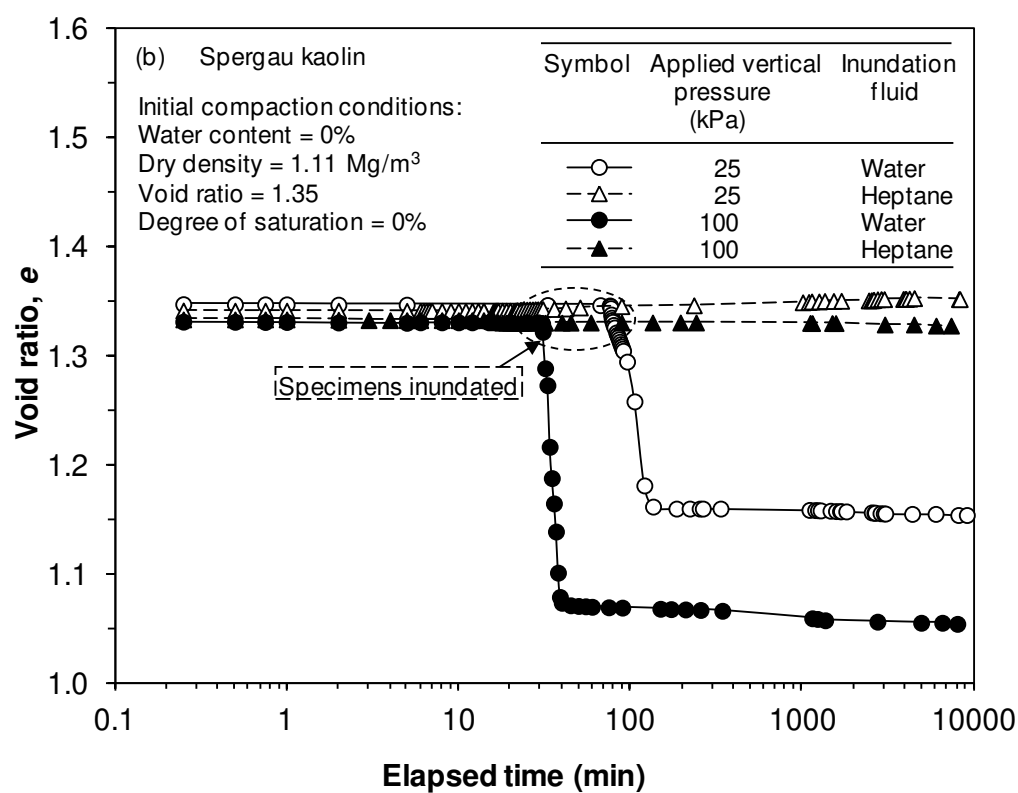
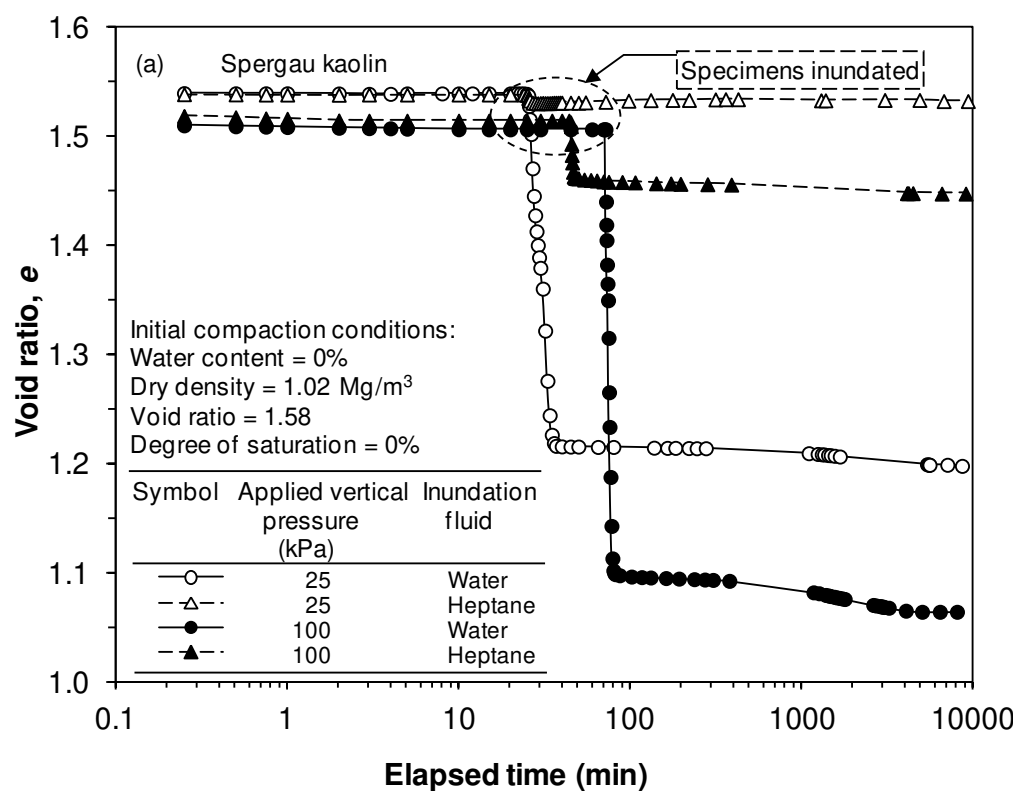


Fig. 1 Time-deformation behaviour of Spergau kaolin specimens (initial water content = 0%)

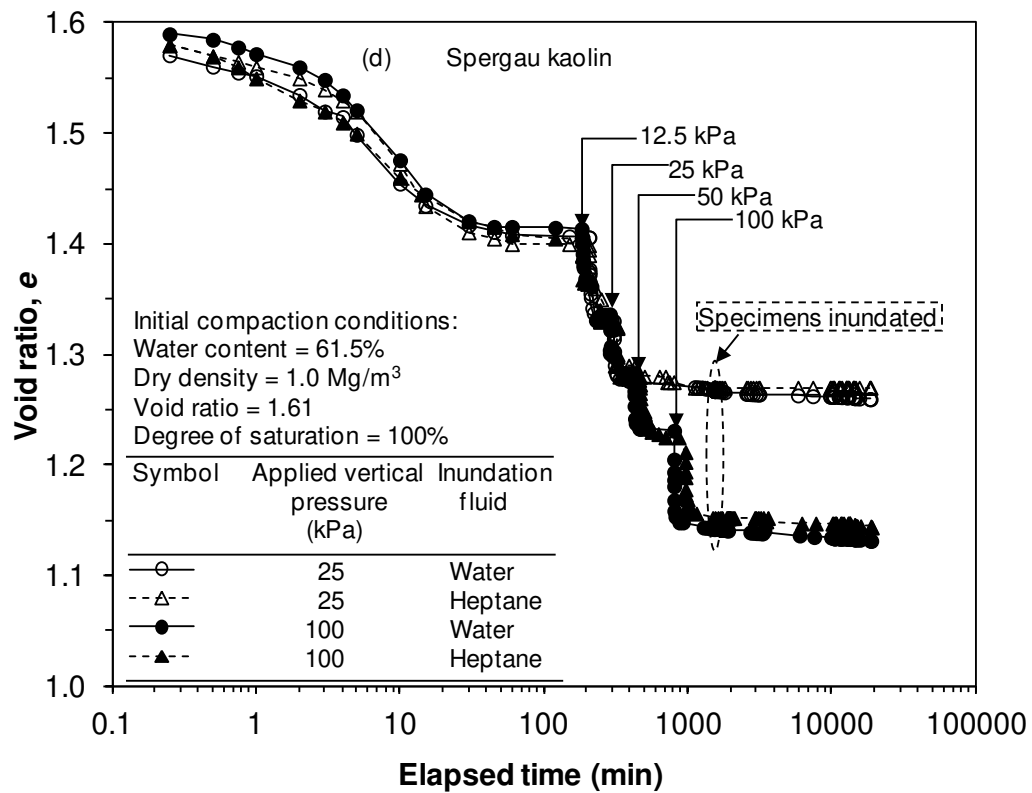
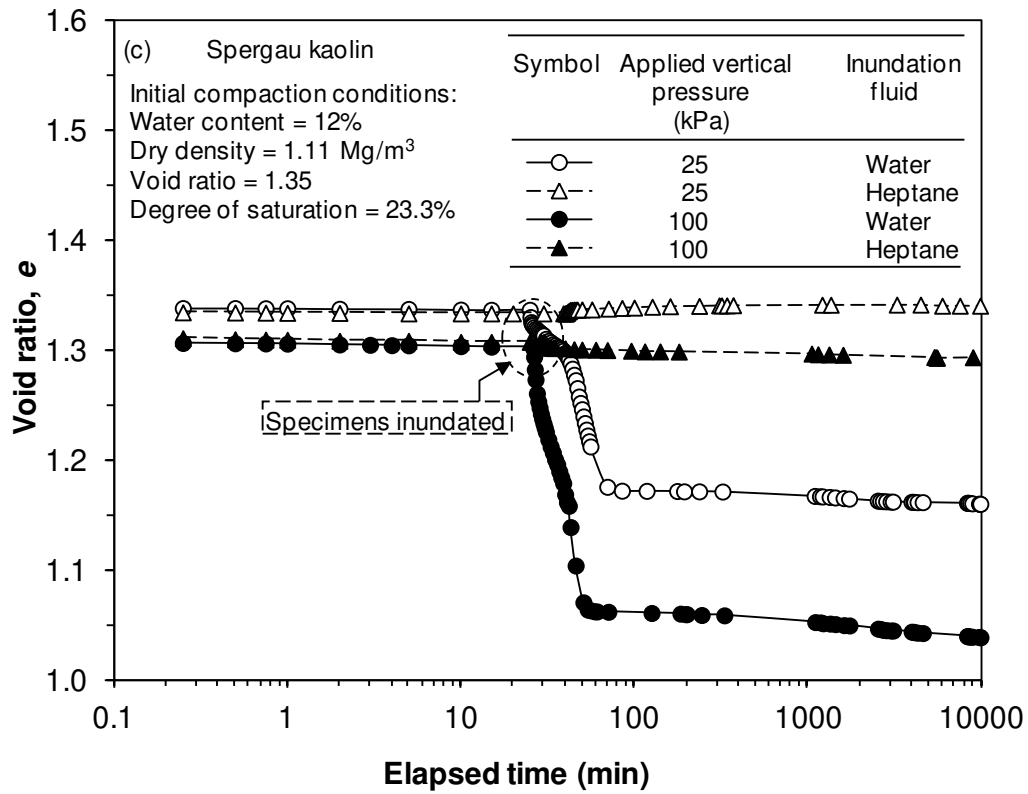
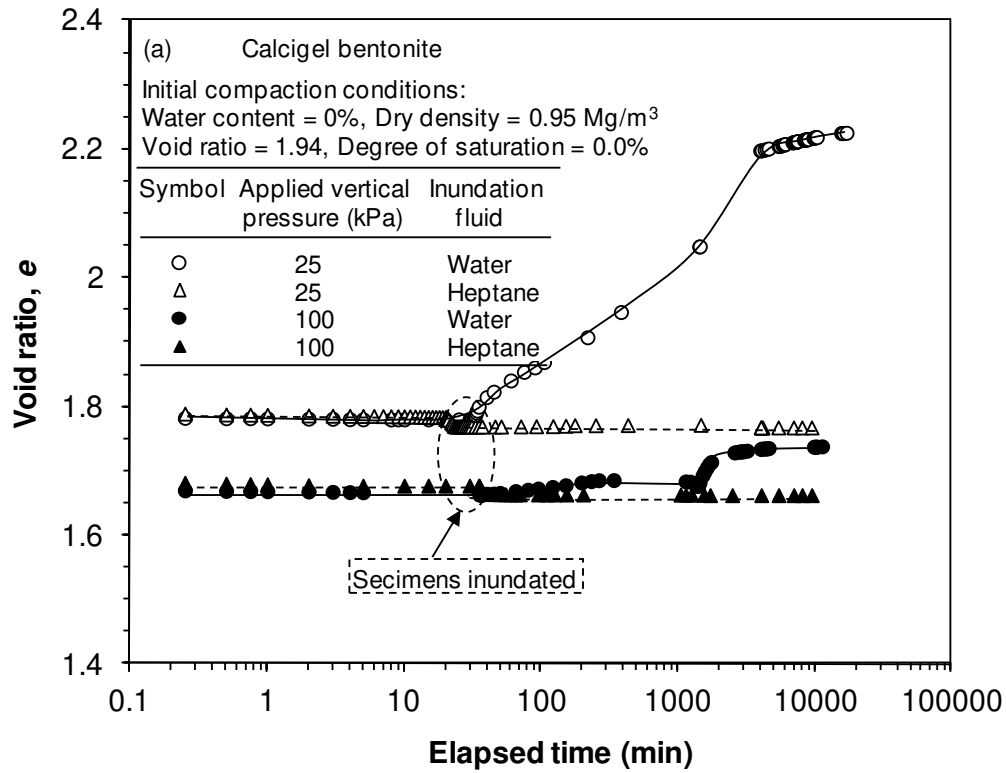
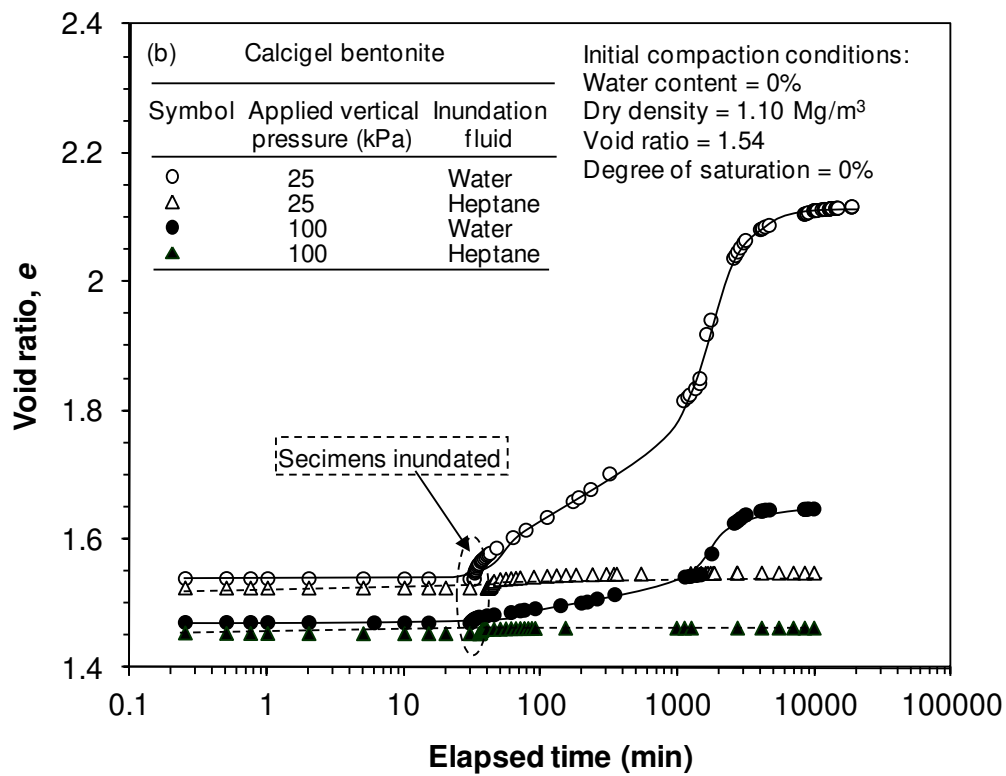


Fig. 2 Time-deformation behaviour of Spergau kaolin specimens with initial water contents of (a) 12% and (b) 61.5%



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517 **Fig. 3** Time-deformation behaviour of Calcigel bentonite specimens (initial water content =
 518 0%)

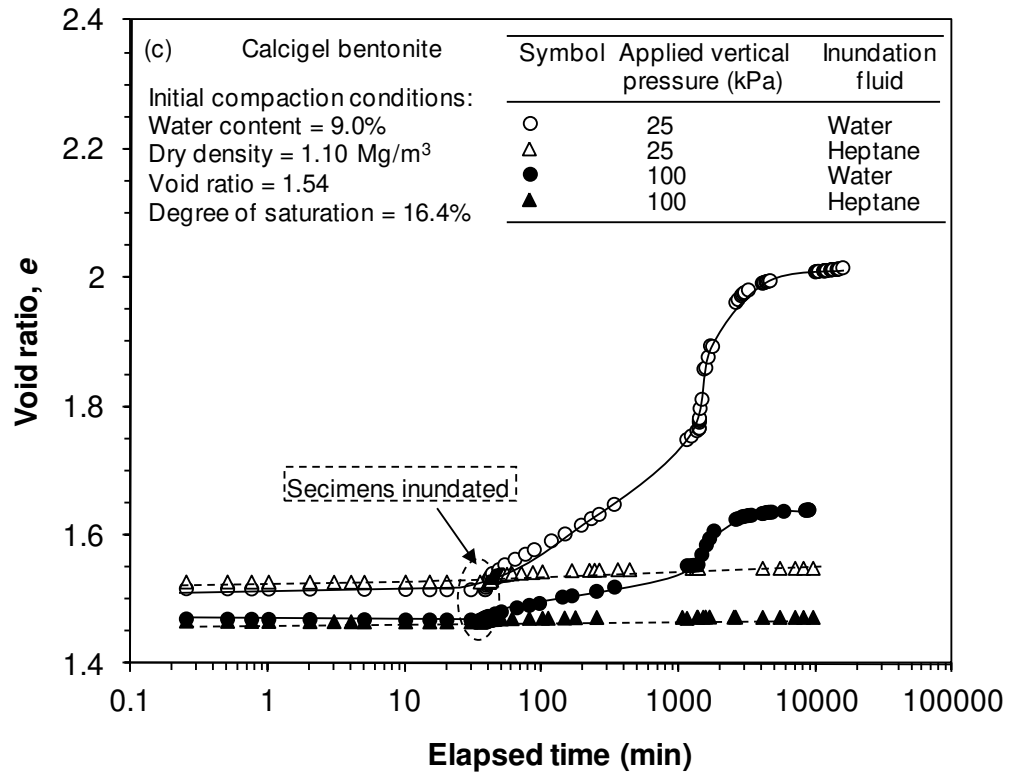


Fig. 4 Time-deformation behaviour of Spergau kaolin specimens (initial water content = 9%)

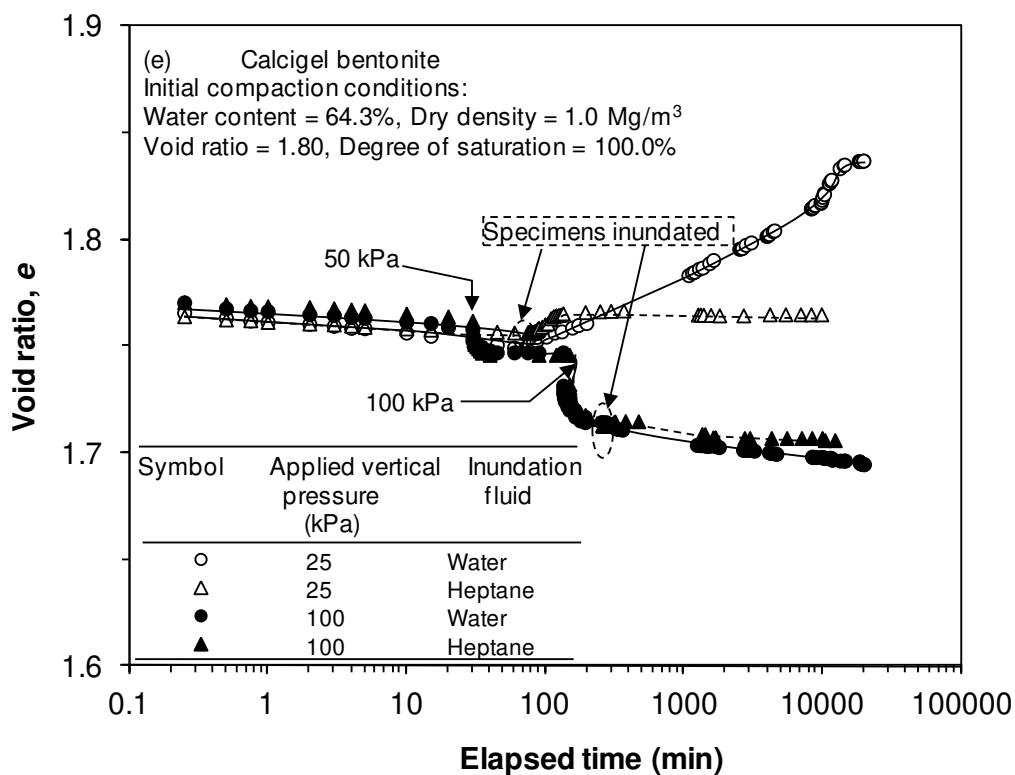
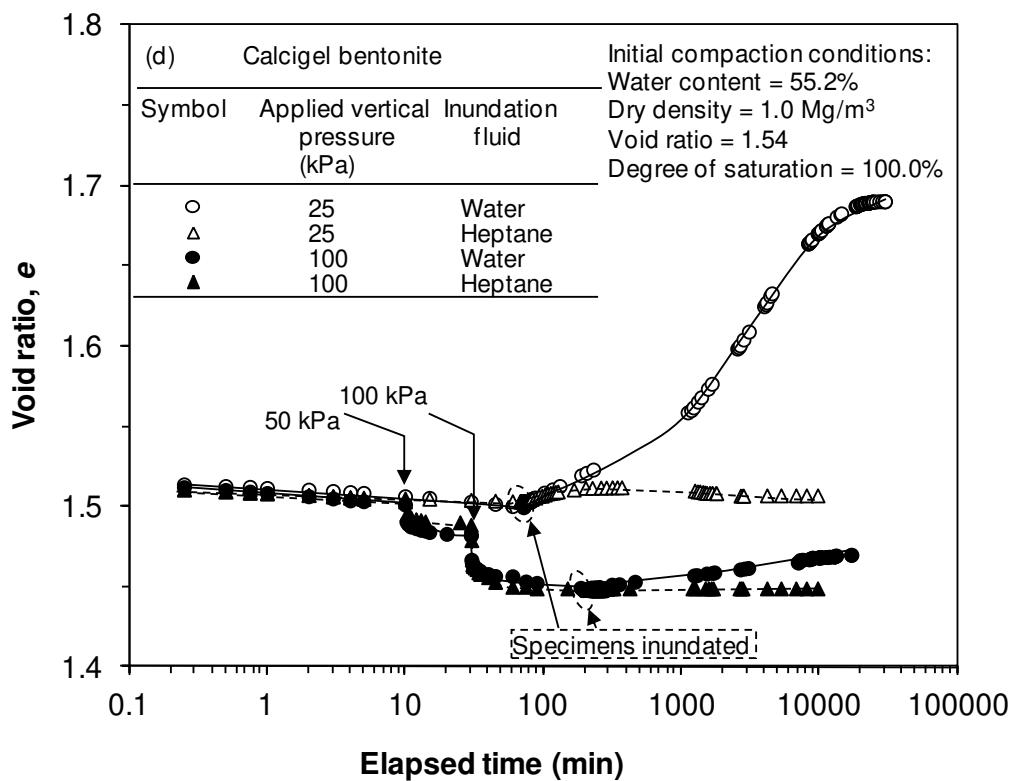


Fig. 5 Time-deformation behaviour of Calcigel bentonite specimens with initial water contents of (a) 55.2% and (b) 64.3%

Volume change behaviour of swelling and non-swelling clays upon inundation with water and a low dielectric constant fluid

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Highlights

- Volume change behaviour of clays with water and heptane as the inundating fluids is presented.
- Mineralogy, dielectric properties, compaction conditions, and stress impact the volume change.
- Mobilised attractive and repulsive forces dictate compression and swelling in unsaturated clays.

Volume change behaviour of swelling and non-swelling clays upon inundation with water and a low dielectric constant fluid

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Abstract: Studies of the volume change behaviour of saturated and unsaturated fine-grained soils upon exposure to various types of fluid are of significant interest while dealing with contaminated soils. In this study, the one-dimensional volume change behaviour of two clays (Spergau kaolin and Calcigel bentonite) with dominant minerals as kaolinite and montmorillonite was studied by inundating several initially unsaturated and saturated clay specimens with water and a non-polar organic liquid (heptane). For both cases, applied vertical pressures of 25 and 100 kPa were considered under oedometric conditions. The magnitude of compression and swelling deformations of the clays were found to be strongly dependent upon the mineralogy of clays, dielectric properties of the pore-fluid, initial compaction conditions, and applied stress during the wetting process. The test results indicated distinct interactions between unsaturated clays and water. Specimens of Spergau kaolin exhibited compression with water, whereas specimens of Calcigel bentonite exhibited swelling. Compression and swelling deformations of the clays with heptane as the inundating liquid remained within about $\pm 1.0\%$ for both clays indicating a very minor interaction between unsaturated clays and molecules of this non-polar organic liquid. The test results emphasized the significance of attractive and repulsive forces and their impact on the volume change behaviour of clays of different mineralogy.

Keywords: minerology of clays; swelling; compression; pore-fluid; waste containment; laboratory tests

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